

Heavy Flavour Production in Two-Photon Collisions at LEP *

SI-2002-3
June 2002

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New results from the experiments ALEPH, DELPHI, L3, and OPAL on heavy quark production in $\gamma\gamma$ collisions are presented. Inclusive charm and bottom production are investigated at LEP 2 energies. The total and differential cross sections for charm quarks are now measured by all four LEP collaborations, the total bottom by two. Charmonia are studied inclusively via the muonic decay of the J/ψ and separated for the resolved and diffractive processes. New results are available for exclusive production of the η_c meson. First searches for exclusive η_b production are presented.

1. Introduction

Inclusive heavy flavour production in two-photon collisions is dominated by two processes, the direct and single-resolved process. It therefore reveals the structure of the photon and is sensitive to its gluon content. At LEP 2 energies direct and the single-resolved processes contribute in equal shares to heavy flavour final states. The charm cross section is about two orders of magnitude larger than the bottom production due to the smaller quark mass and higher electric charge. The large quark mass allows the production of heavy flavour to be calculated in perturbative QCD, where the resolved part also depends on the assumed gluon density of the photon.

The exclusive charmonium production has a diffractive contribution at low p_T^2 of the vector meson (pomeron exchange) and a resolved contribution at high p_T^2 (gluon exchange). The resolved production of J/ψ , when calculated in the nonrelativistic QCD, predicts that the colour-octet contribution dominates. Exclusive charmonia and bottomonia production at LEP 2 provides a precise tool to test QCD at low energies. Their two-photon widths and masses are constraint by approaches used in lattice QCD, nonrelativistic QCD and potential models.

* Presented at the DIS2002 conference in Cracow, Poland; to be published in Acta Physica Polonica B

In this article we summarize the progress made with respect to last year [1, 2] in heavy flavour production in two-photon collisions at LEP 2: improvements, updates and new results are reviewed. A recent more general overview on two-photon physics and the interaction of the photon may be found in Ref. [3].

2. Inclusive Charm Production

2.1. Inclusive D^* Production

All four LEP experiments [4, 5, 6, 7] have measured the inclusive charm production using all [4, 5, 6] or two thirds [7] of their LEP 2 statistics (corresponding to an integrated luminosity of $\approx 700 \text{ pb}^{-1}$) at energies around $\sqrt{s} \approx 200 \text{ GeV}$ with fully reconstructed D^* mesons in no-tag events. The $D^{*\pm}$ mesons are reconstructed via the decay to $D^0\pi^+$, the mass difference of D^* and D^0 providing a clear signal with small background; up to four decay modes of the D^0 are considered.

Three experiments [4, 6, 7] provide differential distributions in pseudo-rapidity. The distributions are found to be flat in this variable, what is in agreement with the expectation for NLO calculations [8] in shape, while in normalisation ALEPH and L3 are in agreement with the massive calculation, the OPAL data prefer the massless calculation. The distribution in transverse momentum to the beam axis as predicted in NLO calculations in the massive approach agrees with the data (Figure 1). The data are more consistent now as compared to last year's preliminary results [1]. A small scatter of the data points in the range $2 \text{ GeV} < p_T < 3 \text{ GeV}$ is still observed, but is within the given errors.

Direct and single-resolved contribution can be separated using the fact that in the resolved one the remnant jet carries away a part of the invariant mass available in the $\gamma\gamma$ collision. Two variables have been used: 1) $x_T = 2p_T^{D^*}/W_{\text{vis}}$, which is the ratio of $p_T^{D^*}$, a measure for the invariant mass of the $c\bar{c}$ system, and the visible invariant mass W_{vis} , a measure for the invariant mass of the $\gamma\gamma$ system; 2) x_γ^{min} , the minimum of $x_\gamma^\pm = \sum_{\text{jets}}(E \pm p_z)/\sum_{\text{part}}(E \pm p_z)$, a measure for the fraction of particles, which do not escape in the remnant jet. The relative contribution $r_{\text{dir}} : r_{\text{res}}$ fitted by the three experiments [4, 5, 7] are in agreement with the prediction of Frixione et al. [8] (70 : 30) and among themselves regarding the slightly different acceptance ranges of the experiments.

2.2. Cross Section as Function of $W_{\gamma\gamma}$

The L3 collaboration has measured the charm cross section as function of the two-photon centre-of-mass energy [9] using the whole LEP 2 data

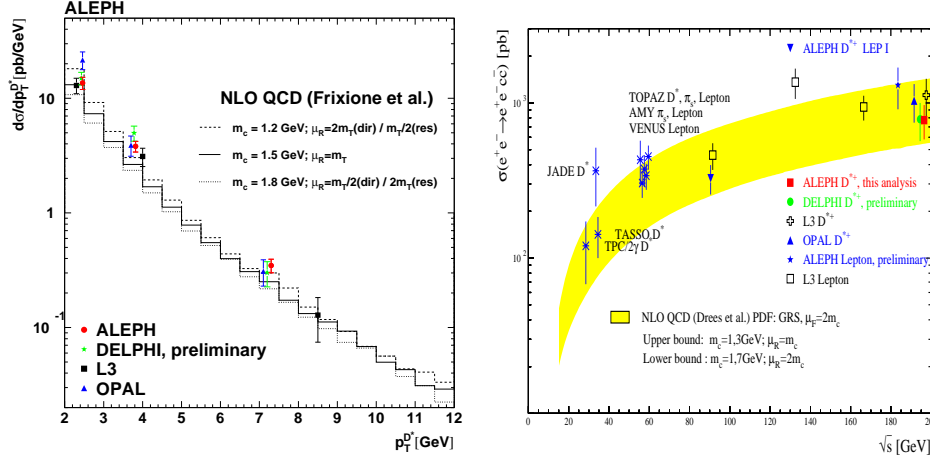


Fig. 1. Differential D^* cross section in Fig. 2. Inclusive charm cross section as function of centre-of-mass energy.

sample. The charm-flavoured quarks are identified by their semi-leptonic decays to electrons. A parameterization of the form $\sigma_{\text{tot}} = As^\varepsilon + Bs^{-\eta}$ (Pomeron + Reggeon) describes the data well. The PYTHIA Monte Carlo clearly fails, predicting only 66% of the total cross section. This may be partially attributed to next-to-leading order corrections, which are not included in PYTHIA. The Pomeron slope fitted from the data is steeper than the rise observed in $\sigma(\gamma\gamma \rightarrow q\bar{q}X)$. NLO order calculations, but using a rather small charm quark mass of 1.2 GeV, are in very good agreement with the data. This also indicates that the resolved contribution, the gluon content of the photon, which dominates at high $W_{\gamma\gamma}$, is needed to explain the data.

2.3. Total Charm Cross Section

Extrapolated to the full phase space, the measurements using the D^* as the charm tag, can be compared to QCD [8] and other measurements [4], see Figure 2. All data are consistent. If only the direct contribution would be considered the prediction at LEP 2 would be lower by a factor two. It should be noted that for the measurements with leptonic final state a light charm quark mass is slightly preferred.

2.4. Charm Structure Function $F_{c,2}^\gamma$

When one of the scattered beam particles is detected, the event can be used to determine the charm structure function $F_{\gamma,c}^2$. With 60 such single-

tagged events with a D^{*+} meson from the full LEP 2 statistics, the OPAL collaboration performed a first measurement in two bins of x with $\langle Q^2 \rangle \approx 20 \text{ GeV}$ [10]. (See Ref. [12] for a general overview on photon structure functions.) The comparison with the calculations shows that a point-like contribution is not sufficient to describe the data. A hadron-like part is needed. The data even exceed the models, though the measurement errors are still too large to be conclusive.

While writing this article, OPAL submitted their result [11] for publication now with a fitted number of 55 D^{*+} mesons, reducing somewhat the discrepancy between data and the calculations at low x .

3. Inclusive Bottom Production

Open bottom production is measured by the L3 and the OPAL collaborations [13] at LEP 2 energies using an integrated luminosity of 400 pb^{-1} . Their analysis procedures exploit the fact, that the momentum as well as the transverse momentum of leptons with respect to the closest jet is higher for muons and electrons from bottom than from background, which is mainly charm. Therefore, leptons with momenta of more than 2 GeV are selected and their momentum distribution with respect to the closest jet (obtained with the JADE jet-algorithm in L3 and KTCLUS in OPAL, while in both experiments the lepton was excluded, when defining the jet) is investigated.

Similar to the studies in charm production, the bottom quarks produced in direct and single resolved events show a different behaviour in the transverse momentum distribution. The variable $x_T^\mu = 2p_T^\mu/W_{\text{vis}}$ is well suited to demonstrate the need for both contributions: the single resolved part at low x_T^μ and the direct part at high x_T^μ . The agreement between data and Monte Carlo simulation is very good.

The total cross section measurements for open bottom production are summarized in Figure 3. The results are compared to NLO calculations [8]. The calculations underestimate the data by a factor three corresponding to three to four standard deviations. See also remarks and discussions in the presentation in Ref. [14].

4. Production of Charmonia and Bottomonia

4.1. Inclusive J/ψ

A first study was performed by DELPHI of inclusive J/ψ production in $\gamma\gamma$ collisions at LEP 2 energies [15]. A clean signal of 36 ± 7 events for $\gamma\gamma \rightarrow J/\psi + X$ is seen, where the J/ψ decays to a muon pair and where X denotes at least two tracks seen in the detector. From a fit of the direct and resolved contribution, as taken from the PYTHIA simulation, a value of $74 \pm$

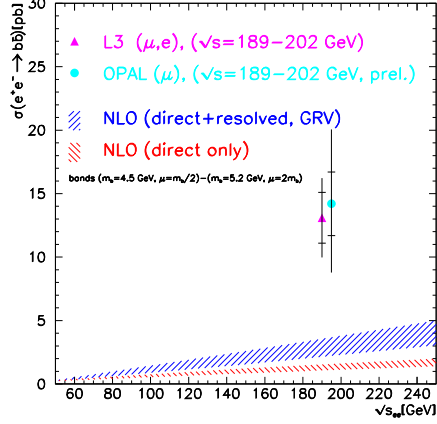


Fig. 3. Inclusive bottom cross section.

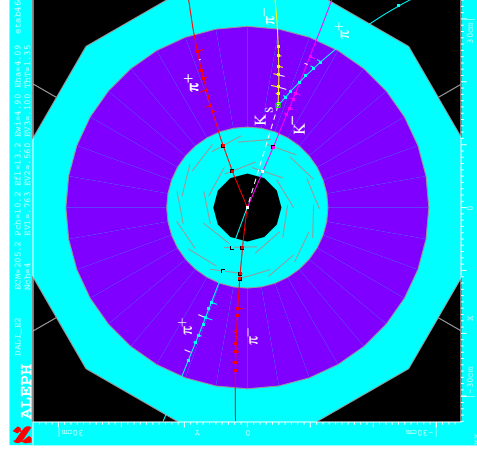


Fig. 4. candidate event.

22% is extracted to originate from the resolved process: a clear indication for the gluon in the photon. In a recent paper the octet production of J/ψ in association with jets has been discussed [16]. It was argued that the singlet production is not sufficient in order to describe the data, but that the octet production is needed for an agreement with the DELPHI measurements. See also Ref. [17] for a discussion of octet production.

4.2. Exclusive η_c

The formation of the η_c in exclusive production in two-photon production is a good test of QCD (See Ref. [18] for a short summary of the present status of studies of exclusive particle production in two-photon events). A preliminary study of η_c at LEP 2 has been contributed to this conference [19]. Nice signals are found in the decay modes of the η_c to $\pi^+\pi^-K^+K^-$, $K^+K^-K^+K^-$, and $K_S K^+\pi^-$. No signal, however, is seen in the $\pi^+\pi^-\pi^+\pi^-$, while for the latter it is also expected, when the branching fraction of Ref. [20] are implied. An upper limit for this channel is given. For the other three a two-photon width is obtained somewhat higher than the world averages [20] and recent measurements at LEP and other colliders [18].

4.3. Exclusive η_b

As reported at last year's DIS conference in Bologna [2], the ALEPH experiment has started a search for the still undiscovered η_b pseudoscalar meson (See Figure 4 for a candidate event). The search has recently been

published [21]; a preliminary result of a search has now also been reported by L3 [22].

Various predictions exist for the mass of the η_b , e.g., from potential models, pQCD, NRQCD, and lattice calculations. While the production can reliably be estimated the branching ratios of the meson have to be guessed. An estimate based on MLLA combined with LPHD and using isospin invariance has been proposed [23] and used by ALEPH. The efficiencies for the decay modes of the η_b under study by ALEPH (four charged particles; or six charged particles) and L3 (two charged particle plus neutral pion or eta; or four charged particles; or six charged particles) are around 13% and 4%, respectively. The experiments would expect about one to two events. The background is estimated to be about one event. ALEPH observes one, L3 observes three events in the signal region from 9.0 GeV to 9.8 GeV. Candidate masses are 9.30 ± 0.03 GeV and 9.49 ± 0.30 GeV, 9.14 ± 0.30 GeV, 9.70 ± 0.30 GeV, respectively. Limits on $\Gamma_{\gamma\gamma}(\eta_b)$ and $\Gamma_{\gamma\gamma}(\eta_b) \times \text{BR}$ have been given, e.g., $\Gamma_{\gamma\gamma}(\eta_b) \times \text{BR}(4\text{cha}) < 48$ eV and $\Gamma_{\gamma\gamma}(\eta_b) \times \text{BR}(6\text{cha}) < 132$ eV by ALEPH.

5. Summary

We summarized the investigations of heavy flavour production in two-photon collisions at LEP. The inclusive charm production has been studied and QCD predictions and experiment are found in agreement for differential distributions such as in pseudorapidity and transverse momentum and total cross section. The dependence on $W_{\gamma\gamma}$ is reproduced by QCD, which requires gluon in the photon. This is also proven by the explicit measurement of the fraction of direct and resolved contribution in no-tag events. The charm structure function $F_{c,2}^\gamma$ shows some deviations, but more statistics is needed.

The inclusive bottom cross section shows a serious problem. The total cross section as predicted by NLO QCD-calculations is too low by a factor three.

Newer measurements on inclusive charmonia clearly show that the colour octet production is needed. While most measurements of exclusive charmonia are in agreement with the world averages some inconsistencies arose, such as in the decay of the η_c to four charged pions. The searches of the η_b in exclusive production from two photons look promising, but other experiments are needed for discovery.

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